

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PROGRESS REPORT

Grant No. NsG 1 - 59

FACILITY FORM 602

N66-85661

(ACCESSION NUMBER)

(THRU)

(CODE)

(PAGES)

(CATEGORY)

CP 63256

(NASA CR OR TMX OR AD NUMBER)

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April 15, 1965

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ABSTRACT submitted to the New York APS Meeting, January 1965.

Excitation of 2^3P and 2^1S States of Helium by
Electron Bombardment.*

Helen Keil Holt and Robert Krotkov
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Helium gas is bombarded by electrons to obtain a beam of metastable atoms which are then analyzed in an inhomogeneous magnetic field and the spatially separated $m = 0$ and ± 1 atoms counted. Taking the cross section for exciting the 2^3S state as known, an upper limit for the 2^1S cross section has been obtained as a function of electron energy. Similarly, upper and lower limits have been found for the 2^3P cross section, also as a function of energy. The lower bound is in rough agreement with the curve derived by Frost and Phelps,¹ while the upper bound lies below the curve calculated by Massey and Moiseiwitsch.² If a plausible but uncertain guess is made about the 2^1S cross section, inferences can be drawn about how the various fine structure sub-states of the 2^3P level are populated by the electron impact. The results so obtained will be related to the well known anomaly in the polarization of light emitted after electron impact.

* Work supported in part by the National Aeronautics and Space Administration.

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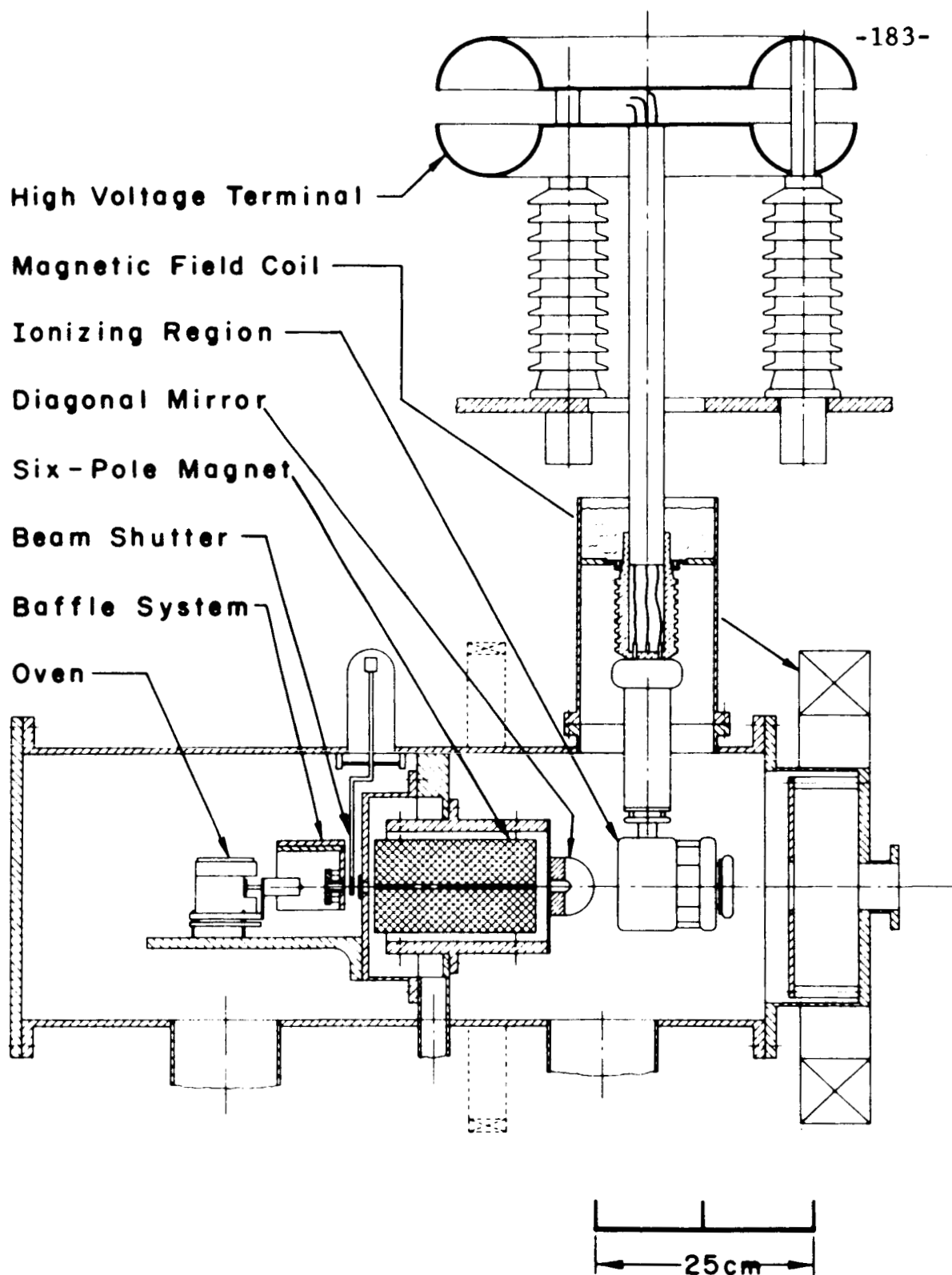


Fig. 2

ABSTRACT submitted to the New York APS Meeting, January, 1965.

part II

Fast H(2S) Production by Charge Exchange in H₂ Gas.*

James E. Bayfield and Robert Krotkov

Yale University.

A beam of fast positive ions accelerated from a radiofrequency hydrogen discharge is passed through 3 to 100 micron cm of H₂ gas. Any 2S state hydrogen atoms contained in the resultant beam emerging from the gas cell are electrostatically quenched and the resultant Lyman alpha photons are detected. At low gas cell pressures approximately 5 out of every 1000 of the fast neutral particles formed by charge pickup in the gas are found to be in the 2S metastable state. The cross section for this charge-exchange process is found to rise from 0.018 \AA^2 per gas atom for incident fast ions of energy 7 keV to 0.024 \AA^2 per gas atom at 21 keV. The absolute values of these cross sections are thought to be reliable to within a factor of three. If the plausible assumption were made that at least half the ion beam were protons, then our result would be that the cross section for production of fast H(2S) atoms by protons incident on H₂ gas is less than $.036 \text{ \AA}^2$ at 7 keV and $.048 \text{ \AA}^2$ at 21 keV.

* Work supported in part by the National Aeronautics and Space Administration.

PART I Electron-Atom Scattering Cross Sections Using Atomic Beam Techniques (R. Krotkov and H. Holt)

Results obtained in this experiment have been reported at the 1965 New York meeting of the American Physical Society.¹ An abstract of the talk delivered there is included with this progress report.

The results obtained may be summarized as follows:

1. The cross section for the process $e^- + \text{He}(1^1S_0) \rightarrow \text{He}(2^1S_0) + e^-$ has been measured for electron energies from threshold (20.6 volts) to about 2 volts above threshold, and the results are shown in Figure 1. This is the first direct measurement of this cross section in this energy range, and the results may be compared with calculations by Massey and Moiseiwitsch² and by Marriott.³ There is agreement to within a factor 2, the theoretical calculations tending to predict cross sections which are greater than the measured values.

2. The cross sections for the process $e^- + \text{He}(1^1S_0) \rightarrow \text{He}(2^3P) + e^-$ has been measured for energies from threshold to about 2 volts above threshold and the results are shown in Figure 2. These experimental results are significantly smaller (by as much as a factor 2) than the theoretical predictions of Massey and Moiseiwitsch,⁴ and are in rough agreement with an estimate of the cross section derived by Frost and Phelps⁵ through an indirect method.

3. A measurement has been made of the difference in population between the $m = 0$ and $|m| = 1$ magnetic substates of the 2^3S_1 metastable state, when this state is populated by cascade

from the 2^3P state (which is itself made by electron bombardment). The measurements extend from threshold to approximately two volts above threshold, and are closely related to the well-known anomaly in the polarization of collision light, which has been discussed by many authors.⁶ Over the 2 volt energy range, our measurements yield a population difference which is an approximately constant fraction of the 2^3P cross section. This fraction is about a factor 5 lower than the expected value at threshold. This is in qualitative agreement with the results obtained in the optical experiments on collision light and tends to confirm the existence of an apparent anomaly, at least when the experiments are done with an electron energy resolution of about half a volt.

Although the experiment has been substantially completed, a number of points remain to be examined more carefully, and further measurements are in progress on pressure effects and on the dependence of the 2^1S signal on applied electric fields. It is not expected that the results described above will be affected in any important way.

PART II Charge Exchange Cross Sections (J.E. Bayfield and
R. Krotkov)

II. 1. Introduction

Since the last progress report, research has continued on the measurement of cross sections for various processes occurring when protons pass through molecular hydrogen gas. Some of the results have been reported at the New York meeting of the APS.⁷ A copy of the abstract is included with this progress report.

The charge exchange process for the system $H^+(\text{fast}) + H_2 \rightarrow H^0(\text{fast}) + \text{slow products}$ has been extensively studied by many authors at proton energies in the range 1 to 50 kev.⁸ Until recently the distribution of the reaction products in their various energy states has not been studied. Our interest lies in the various excited states of the fast atomic hydrogen beam produced by charge exchange. There is reason to expect that targets other than hydrogen gas might lead to intense beams of certain excited states, but so far we have used molecular hydrogen only. The excited states of interest have been the 2S metastable state and highly excited states with principal quantum numbers in the range $n = 7$ to $n = 30$. Charge exchange processes leading to these states have also been studied by other workers,⁹ but the measurements have been much less extensive than those reviewed in reference 8.

Our interest in production of excited states arises from two sources: First, these are produced in interactions between simple systems so that the results can, in principle, be calculated¹⁰ and compared with experiment. Second, an intense beam of metastable hydrogen atoms is of particular interest in that not only can the cross section for production be compared with a theoretical prediction,¹⁰ but also such a beam can be used for spectroscopic and other studies no matter how it is produced, provided only that it is sufficiently intense. In particular, our preliminary measurement quoted in the progress report of August 1963 indicate that the metastable beam produced by passing fast protons through molecular hydrogen can be made a million times more intense than that used by Lamb¹¹ in his experiments on fine

structure of the $n = 2$ state of atomic hydrogen, including the Lamb shift. This beam will probably make it possible to re-measure this fine structure to an accuracy at least as great as, and probably greater than, that achieved by Lamb, and so possibly obtained improved values of the fine structure constant and of the Lamb shift.

II. 2. H(2S) Metastable Production

Research has continued on the yield of fast metastable 2S hydrogen atoms produced by charge exchange. Improved vacuum conditions in the detection chamber have improved the peak metastable quenching signal to background ratio from 1.1 to 30. Many tests have been made to assure us that the signal observed possesses all the special properties of a true metastable signal. The signal is proportional to incident fast proton current. It is proportional to charge exchange gas cell pressure for low pressures. Electric quenching both before and in the detection region exhibits the proper exponential behavior, the exponent being proportional to the square of the quenching voltage and inversely proportional to the square root of the kinetic energy of the fast metastables. The relative yield of metastables at a gas cell pressure-length product $p_l = 20 \pm 2$ micron Hg cm has been measured as a function of incident proton energy from 7 to 21 kev. The result is shown in Fig. 3. This curve is the relative metastable production cross section curve insofar as collisional metastable destruction is negligible at $p_l = 20$ micron -cm over the stated energy range. We are as yet not certain of this, and data will be taken at lower values of p_l , where we are certain

that signal is proportional to pressure at all energies. Several ways of improving our knowledge of the absolute cross section are being tried. Measurements using target gases other than molecular hydrogen are planned.

II. 3. Highly Excited State Production

Our interest in highly excited states arises from calculations of Butler, Johnson and May,¹² which predict a peak in the production of such states by charge exchange at a proton energy such that the incident proton and the atomic electrons of the gas molecules have approximately the same velocity (i.e. proton energies of about 20 kev). We have looked for this resonance experimentally.

The apparatus consisted of a radio-frequency gas discharge proton source, proton beam acceleration electrodes, a gas-filled charge-exchange cell, a subsequent proton beam removal region, a detector of highly excited states, and a Faraday cup to measure the strength of the initial proton beam. Molecular hydrogen was used in the gas cell. The highly excited atoms were detected by ionizing them and collecting the resulting fast protons on a metal plate or in a Faraday cup. Two methods of ionization were used, first by passing the beam through a strong electric field directed parallel to the beam particles velocity (electrostatic ionization experiment) and second, by passing the beam to be analyzed through a transverse magnetic field, ionization being accomplished by the resulting Lorentz force (magnetic ionization experiment).

In the runs using electrostatic ionization, the current of detected fast protons amounted to $\leq 0.6\%$ of the initial proton beam for proton energies ≤ 24 kev and electric fields $\leq 180 \frac{\text{kv}}{\text{cm}}$. The current of such fast protons as a function of electric ionizing field was as shown in Fig. 4, taken at 12.5 kev incident proton beam energy. The bumps on this curve suggest that states of ever decreasing, neighboring principal quantum number are being ionized, but this interpretation has not been firmly established. For a fixed ionizing electric field strength of $175 \pm 10 \frac{\text{kv}}{\text{cm}}$, the yield of fast protons as a function of incident proton energy appeared to rise slowly over the energy range 8.5 to 24 kev, as shown in Fig. 5. This curve would be a measure of the energy dependence of the highly excited state yield at gas cell parameters $p \approx 150$ micron cm in the absence of excessive ion focusing properties of the ionizing electric field. Although ion defocusing in this field is not expected to have been serious, this must be verified, and a translateable Faraday cup assembly has been made to determine the angular distribution of the fast ions made in the ionizing region.

We can say that the yield of fast protons as a function of incident proton energy is $3.5 \pm 2.5 \times 10^{-3}$ of the incident proton current. This is comparable in magnitude to results by Futch and Damm⁹ and Sweetman,⁹ at incident proton energies much higher than that of the resonance predicted theoretically.

The fast protons might presumably have been produced by collisional stripping of the fast neutral beam atoms by background gas molecules. The background pressure was 2×10^{-5} Torr H_2 ,

the stripping cross section over the energy range of interest is $6 \pm 2 \times 10^{-17} \text{ cm}^2/\text{atom}$, and hence the expected number of protons due to stripping is only 3×10^{-4} of the incident proton beam. Thus only 10% or so of our fast proton signal from the electric ionizing region could have been due to collisional stripping.

Theoretical calculations¹³ indicate that the electric ionization experiment was capable of detecting hydrogen atoms with principle quantum numbers $9 \leq n \leq 15$ with 100% efficiency, and $15 \leq n \leq 28$ with reduced efficiency. The lower limit in n was determined by the maximum ionizing field available, while the upper limit was determined by the magnitude of the electric field needed in the removal region in order to completely stop all primary fast protons from entering the neutral atom ionization region. Reduced efficiency for the larger n values was due to premature ionization and subsequent removal in the primary proton removal field.

In view of the instrumental problem indicated above for the electrostatic ionization scheme for detecting fast highly excited neutral hydrogen atoms, we performed an experiment using instead, the magnetic ionization scheme. The magnetic field used had no focusing properties of any important amount; fast protons produced in this field traveled in circular paths and were collected on a metal plate placed several cm below the beam. Slow ions and electrons were removed by a small electric field directed sideways to the beam.

In this experiment, the current of fast protons possibly due to Lorentz ionization of excited neutrals amounted to $3.5 \pm$

1.0×10^{-5} of the incident proton beam over the energy range 7.5 to 23 kev incident proton energy and was independent of energy to the uncertainty indicated. The magnetic field used was 4400 gauss, which was strong enough to ionize atoms with principal quantum numbers $n \geq 15$. On the other hand, atoms with principal quantum numbers $n \geq 25$ would have been ionized in the retarding field used to stop the residual primary proton beam coming from the gas cell, and hence would never have been detected. Hence the experiment was sensitive only to highly excited atoms with $15 \leq n \leq 25$, and with efficiency of 10% or perhaps somewhat less. If the observed current of fast protons indicated above were entirely due to Lorentz ionization atoms having principal quantum numbers in the range $15 \leq n \leq 25$, the cross section for production of these would be 10^{-15} cm^2 . This is the most that can be reliably extracted from this experiment, using the present magnet. Actually the number of Lorentz ionizable atoms might have been much less than indicated, since fast protons are also produced by collisional stripping. It is estimated that the number of fast protons so produced would be about equal to the number of fast protons actually seen.

In the calculations of Butler, Johnson and May,¹² the cross section for production of excited states in the range $10 \leq n \leq 30$ rises by a factor of 50 in the region of the resonance. This is a huge variation; both of our experiments should have been capable of seeing the effects of this use. Hence it would appear that our experimental results do not confirm the calculations of reference 12.

However, it should be emphasized that in the more reliable magnetic experiment, the background pressure was high enough that fast protons produced by stripping of fast neutral beam atoms masked the signal of Lorentz ionized atoms we desired to see. Fundamentally the same difficulty plagued the earlier experiments on production of $n=2$ metastable hydrogen atoms. Effects due to the background pressure in those experiments again tended to mask the signal we were trying to see.

After completion of the experiments on beams of highly excited atoms described above, considerable effort and time were devoted to designing a charge exchange apparatus which would eliminate the background pressure problems and produce "clean" cross section measurements. This design has been completed and further progress awaits procurement of this apparatus, which is now on order. The new design incorporates extensive differential pumping to keep the pressure in the detection region low, and also includes an improved beam tube which should allow us to go to higher proton energies (up to 50 kev). Magnetic analysis of the beam from the ion source is provided for. The apparatus is also designed so that the spectroscopic experiments on the $n=2$ state of atomic hydrogen could be made on it by simply adding suitable magnetic and r.f field regions. While awaiting delivery, an experiment has been set up with the aid of an undergraduate at Yale, Mr. D. E. Oates, to measure the cross section for production of metastable hydrogen atoms in collisions between fast H atoms in the ground state and various target gases. The apparatus has been assembled and a beam obtained; measurements will commence very shortly.

PART III Polarized Electrons (W. Raith, R. Long, V.W. Hughes)

Progress on this experiment will be summarized in a paper to be presented at the IVth International Conference on the Physics of Electronic and Atomic Collisions, to be held August 2-6 at Université Laval, Quebec, Canada. An abstract of this paper is enclosed. Mr. Robert Long's Ph.D. thesis research was done on this experiment and has now been completed.

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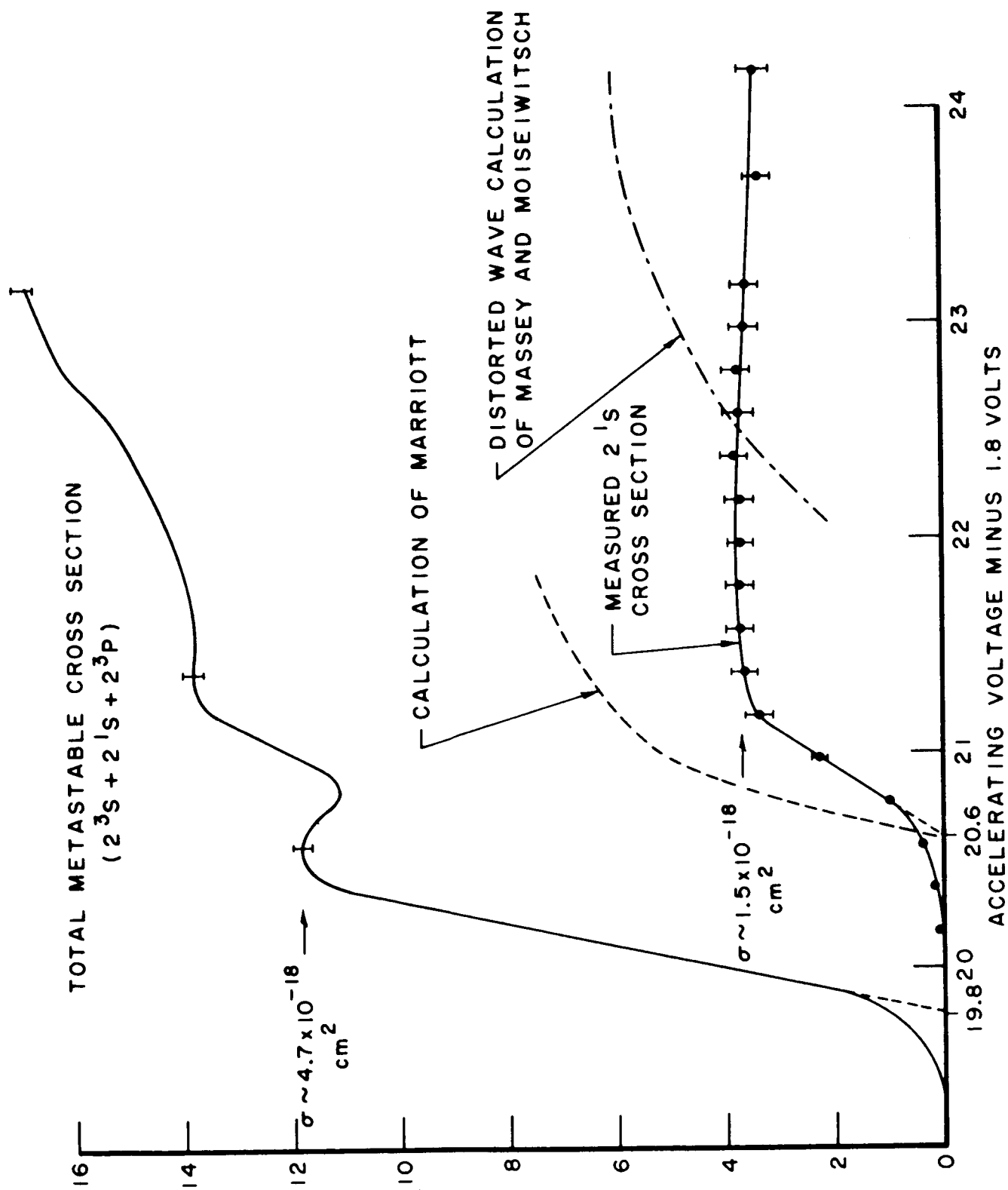


Fig. 1

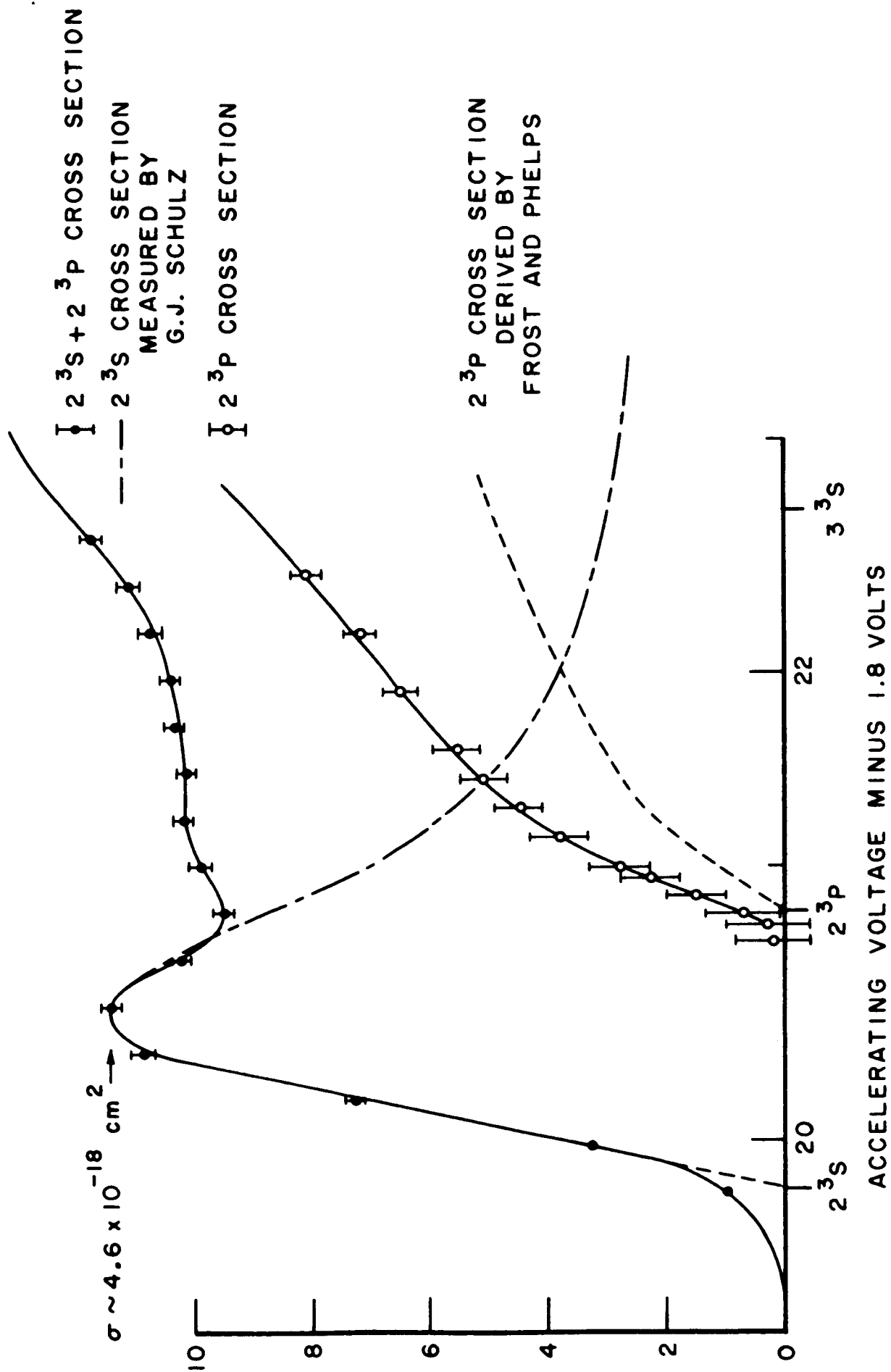


Fig.2

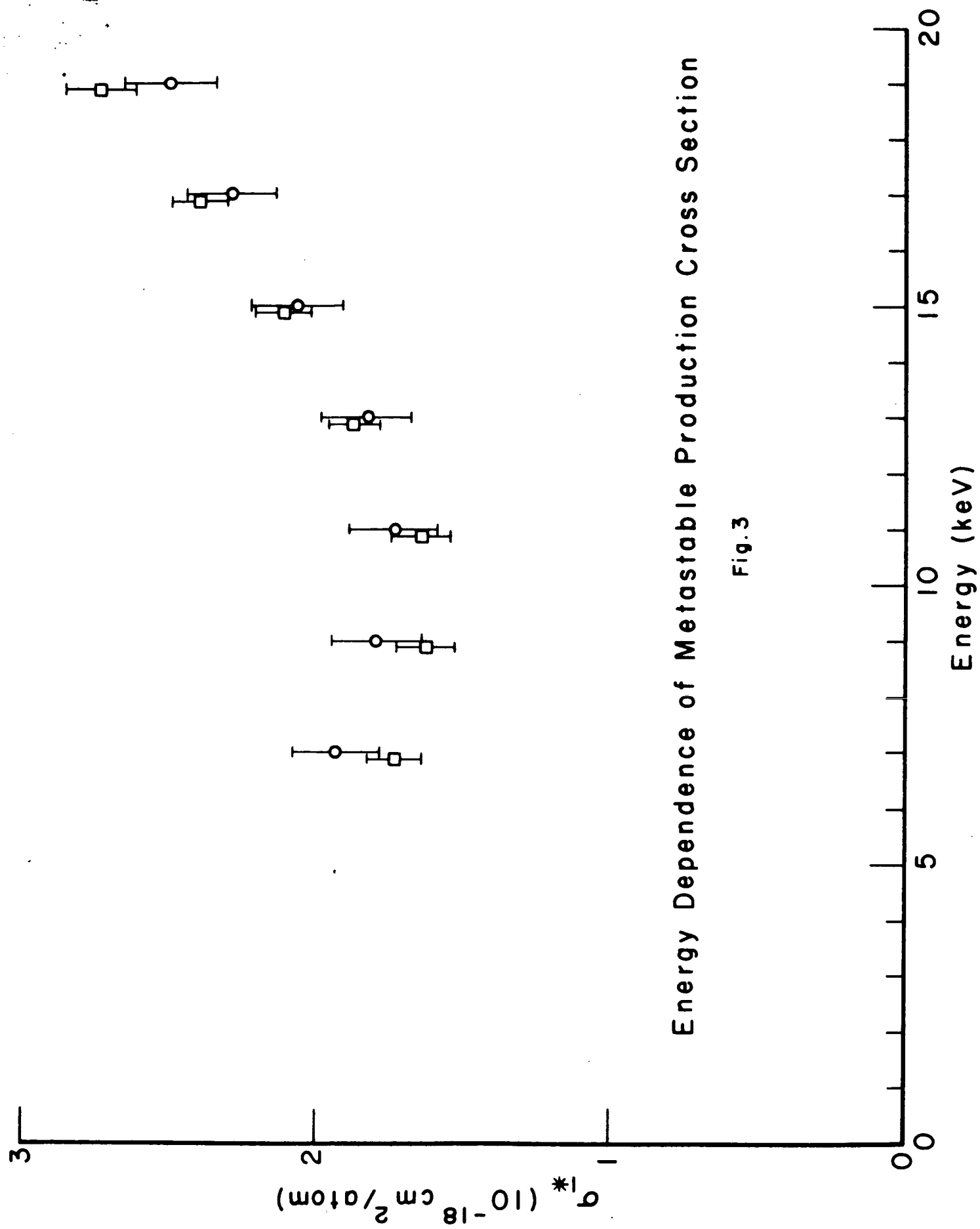


Fig. 4

Ionization of highly excited hydrogen atoms
by an electric field.

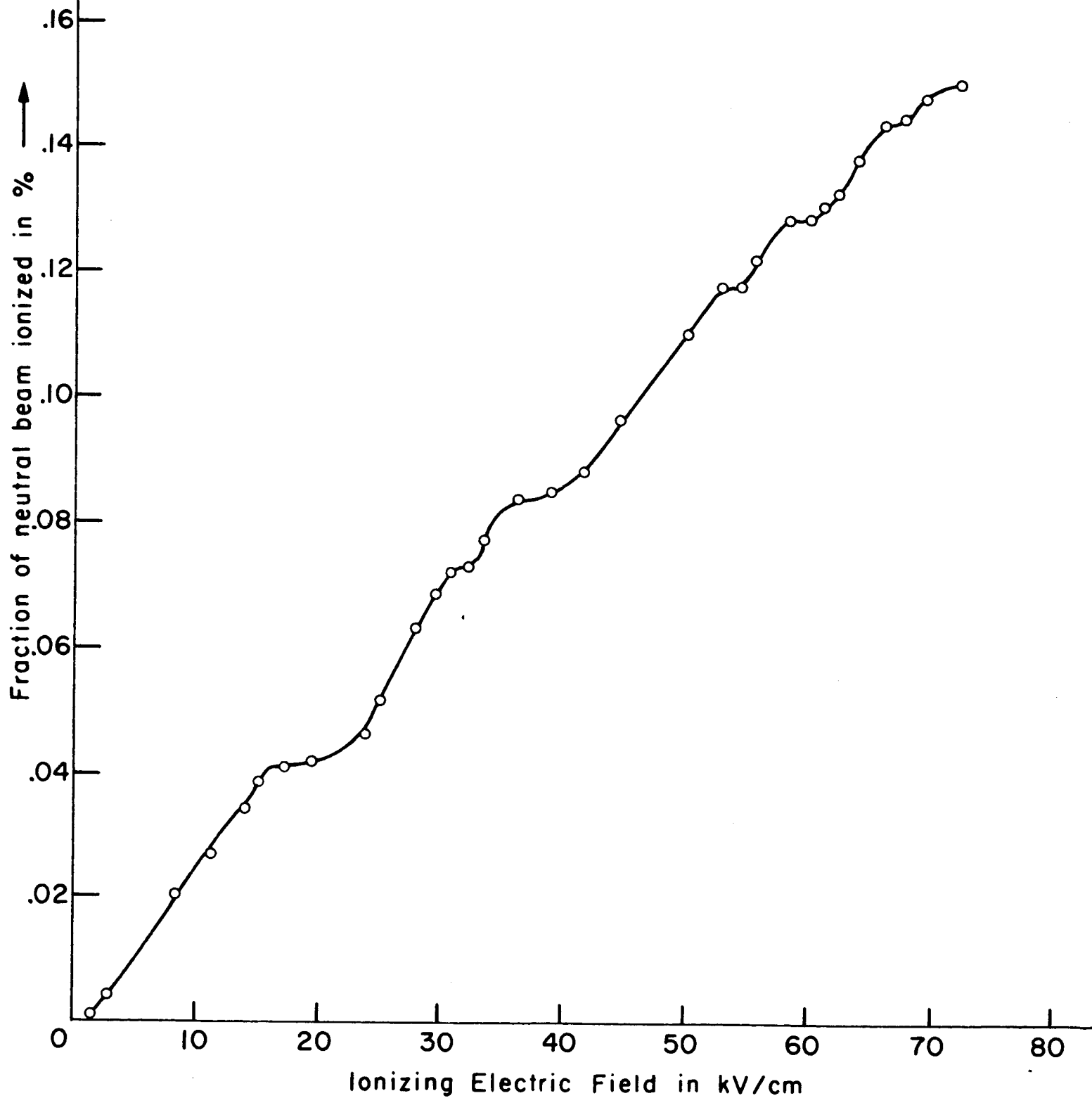
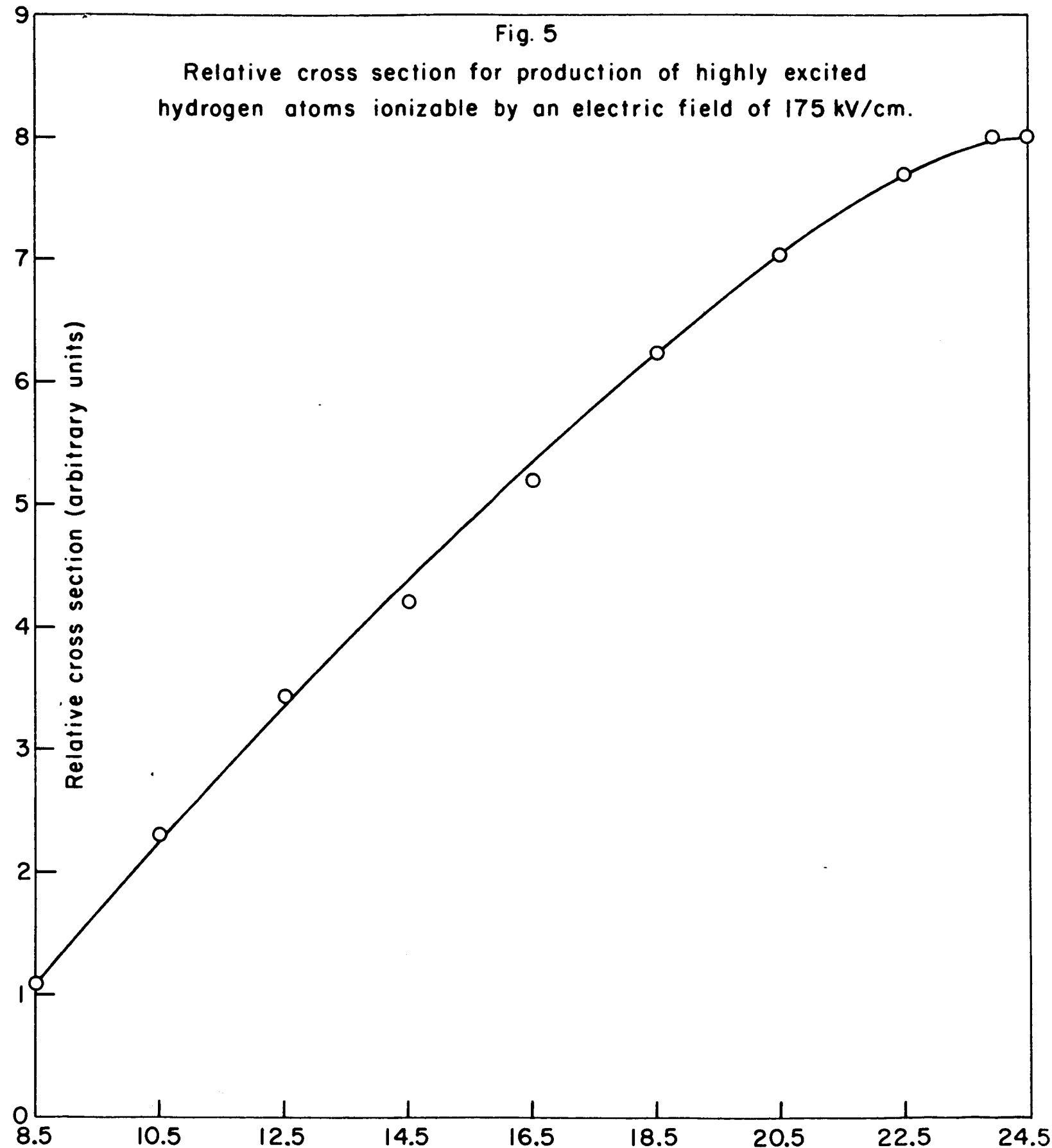


Fig. 5

Relative cross section for production of highly excited hydrogen atoms ionizable by an electric field of 175 kV/cm.

Relative cross section (arbitrary units)

BEAM ENERGY keV →



Submitted to the IVth International Conference on Physics of Electronic and Atomic Collisions, Laval University, Quebec, Canada.
August 2-6, 1965.

Polarized Electrons from a Polarized Atomic Beam*

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Introduction: A source of low energy polarized electrons with narrow energy distribution will be useful for the study of spin-dependent electron-atom interactions. Some possible experiments with polarized electrons include resonant elastic scattering from noble gas atoms¹ to study the spin-orbit interaction and scattering from polarized beams of hydrogen or other atoms to study separately the singlet and triplet scattering parameters. Various methods for producing polarized electrons, other than by beta-decay or Mott scattering, have been investigated. The experiment we report involves the production of polarized electrons through the photoionization of a polarized atomic beam.² The main purpose of our experiment was to study this method of producing polarized electrons rather than to maximize the current and polarization. The theoretically expected electron polarization was obtained after two unanticipated depolarization effects were eliminated.

The Method:³ By deflection in a strong inhomogeneous six-pole magnetic field⁴ ground state alkali atoms with $m_J = +1/2$ are selected (m_J = magnetic quantum number for electronic angular momentum). Then these atoms having a polarization P_a close to unity enter the photoionization region with the magnetic field H_0 along the axis of propagation. The atoms change adiabatically into the lower field states characteristic of H_0 where the electronic polarization $P = f(H_0) \cdot P_a$ is

smaller than P_a because of the hfs coupling of the electronic spin and the nuclear spin (see Figure 1). Photoionization is predominantly an electric dipole transition and especially for light alkali atoms no important spin-orbit interaction in the final state should occur,⁵ so that the polarization of the photoelectrons should equal the electronic polarization P of the atoms. Potassium was chosen as the alkali atom because of its relatively small hfs interaction and relatively low photoionization threshold energy corresponding to $\lambda = 2856\text{\AA}$.

Description of the Apparatus: The polarized electron source is shown in Fig. 2. The six-pole magnet is a permanent magnet with a peak field at the pole face of about 9000G, a gap diameter of $1/8$ " and a length of 7". The light source is a mercury high-pressure arc (Oaram HBO 200W). The arc image is formed with a spherical mirror and a diagonal mirror in the ionization region which consists of two cylindrical electrodes with a suitable bias voltage between them and with both electrodes at a potential of -120 kV, which was required for the analysis of the electron polarization. The axial magnetic field in this region is 90G, and the focusing properties of the electric and magnetic fields serve to discriminate against all photoelectrons emitted from the electrodes. The electron polarization was determined by Mott scattering from gold after the longitudinal electron polarization was converted into transverse polarization by an electrostatic deflector.⁶

Results: The first polarization measurements showed a rapid decrease of the electron polarization with increase of oven temperature. This effect was due to photoelectrons from K_2 molecules in the beam.⁷ In saturated potassium vapor the molecular fraction increases with temperature; atomic beam measurements⁸ gave fractions of 1.3×10^{-3} to 2.0×10^{-3} in the temperature range of interest from 600 to 650°K. The large contribution of photoelectrons from this small fraction of molecules is partially explained by the large photoabsorption cross section of K_2 ,⁽⁹⁾ and in addition the ionization potential of K_2 may be smaller than that of the K atom so that more photons from the light source may be able to ionize the molecules. The K_2 content in the beam was eliminated by thermal dissociation of the molecules in a long tube attached to the oven exit and heated to about 1000°K.

Even with the K_2 content in the beam eliminated the measured electron polarization was smaller than the theoretical value by about 11%. We found that this discrepancy was due to photoelectrons produced in a two-step photoionization process of K in which the first step is that from 4S to 5P and the second step is that from 5P to the continuum. The first step is very probable because the wavelengths for the 4S \rightarrow 5P transition are 4045 and 4048⁰A and these coincide with an intense line of the mercury high-pressure arc; the second transition can be induced by photons with wavelengths shorter than 9700⁰ A. Photoelectrons produced by this two-step process have a smaller polarization due to depolarization caused by the fine structure interaction in the 5P state. Photoelectrons from the two-step photoionization process were eliminated by using a nickel sulfate

- solution filter¹⁰ which does not transmit the resonance line. The measured electron polarization was $P_{\text{meas}} = 0.58 \pm 0.03$ where the stated error is the statistical counting error of one standard deviation. This value agrees with the theoretical value of $P=0.56 \pm 0.02$ where the stated error is due to measurement and inhomogeneity of the magnetic field in the ionizing region.

The maximum current of polarized electrons obtained was 10^{-12}A or 6×10^6 electrons/sec. This value corresponded to a flux of polarized K atoms in the ionization region of $1.2 \times 10^{14}/\text{sec}$ and a photoionization probability of 5×10^{-8} . The latter figure agrees with a rough calculation based on lamp data, photoionization cross section, atomic velocity and geometry.

Both the achieved electron polarization and the current are not representative of the ultimate capacities of this method. Since the polarization obtained with the rather low ionizer field of 90G agrees with the theoretical value, a higher field of about 400G can confidently be expected to yield a polarization of 0.95 (cf. Fig. 1). Increase in beam intensity can be expected with the use of different light sources or other alkali atoms. Utilization of the two-step photoionization process together with polarized light appears promising. The use of a jet atomic beam can be considered.¹¹

The energy distribution of the electrons was not measured in our experiment and no attempt was made to minimize the potential gradient in the ionization region. However, the only fundamental limit to achieving a small energy spread is that due to the energy distribution of the photons.

Figure Captions

- Fig. 1. Calculated function $f(H_0)$ vs magnetic field H_0 for Li^6 and K^{39} .
- Fig. 2. Cross section of the apparatus for production of polarized electrons.

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- * This research has been supported in part by the Office of Naval Research and by the National Aeronautics and Space Administration.
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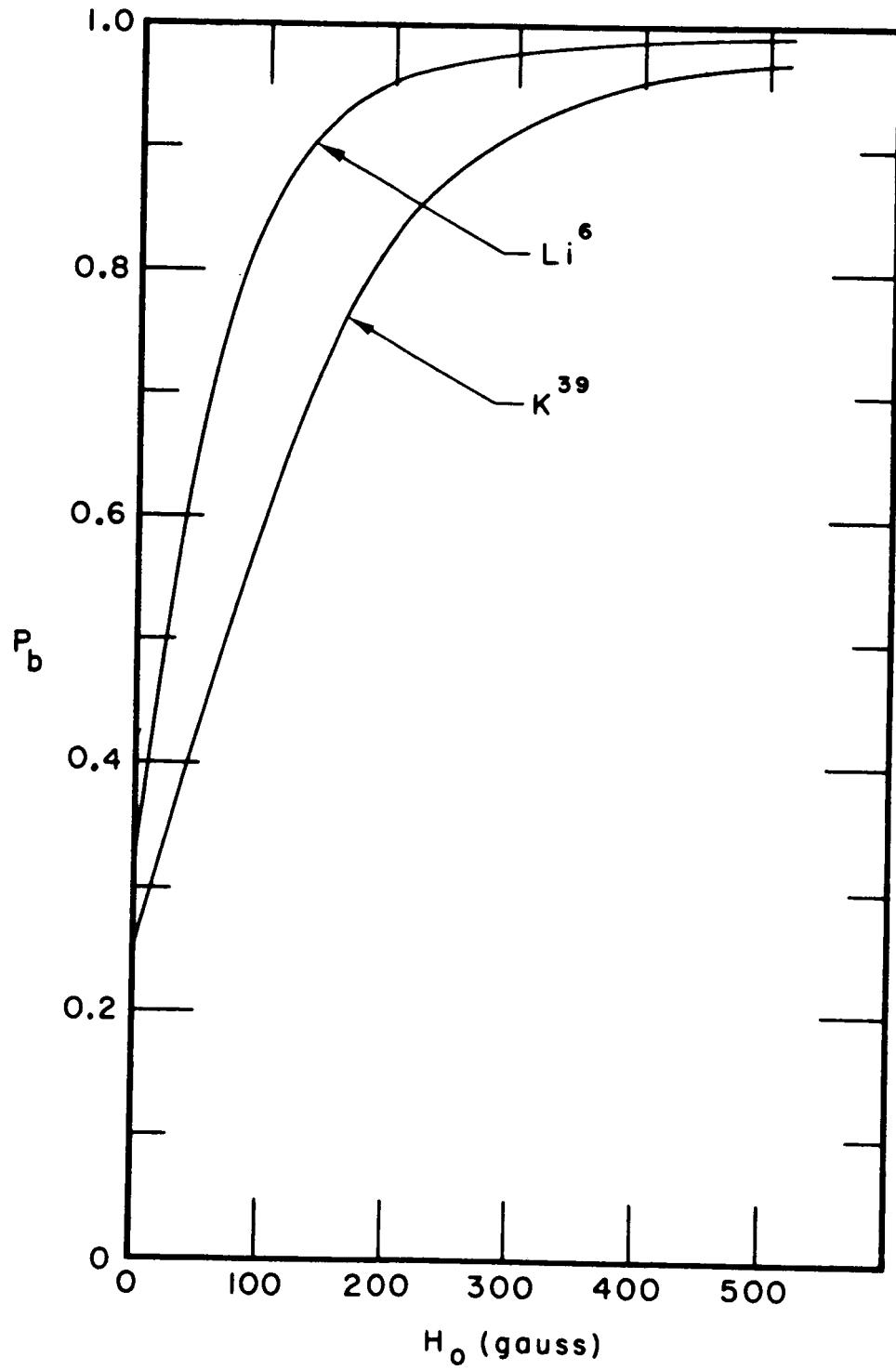


Fig. 1